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A Comparison of Fluidic and Physical Obstacles for Deflagration-to-Detonation Transition

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A *fluidic* obstacle has been proposed as an alternative to conventional deflagration-to-detonation transition (DDT) enhancement devices for use in a Pulsed Detonation Engine (PDE). Experimental results have been obtained utilizing unsteady reacting and steady non-reacting flow to gain insight on the relative performance of a *fluidic* obstacle. Using stoichiometric premixed hydrogen-air, transition to detonation has been achieved using solely a *fluidic* obstacle with comparable DDT distances to that of a physical orifice plate. Flame acceleration is achieved due to the intense turbulent mixing characteristics inherent of a high-velocity jet and the blockage created by the *virtual* obstacle. Turbulence intensity (T.I.) measurements, taken downstream of both obstacles with hot-film anemometry during non-reacting steady flow, show a conservative trend that a *fluidic* obstacle produces approximately a 240% increase in turbulence intensity compared to that of a physical obstacle. Ignition times were reduced approximately 45%, attributable to the increase in upstream T.I. levels relative to the fluidic obstacle during the fill portion of the PDE's cycle. Transition to detonation was obtained for injection compositions of both premixed stoichiometric hydrogen-air and pure air.

Nomenclature

BR	=	blockage ratio
CJ	=	Chapman-Jouguet
DDT	=	deflagration-to-detonation transition
fluidic	=	consisting of fluid, created from a jet
JICF	=	jet in crossflow
MR	=	momentum ratio
PDE	=	pulse detonation engine
physical	=	solid and stationary
SWACER	=	shock-wave amplification by coherent energy release

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T.I. = turbulence intensity
U = mean velocity
u' = root-mean-square of the mean velocity

I. Introduction

THE pulse detonation engine (PDE) has been proposed as a viable replacement for current propulsion and power generation systems that employ constant pressure combustion[1]. The high thermodynamic efficiency and simplistic design of the PDE make it an attractive area of research within the combustion community[2]. There are still several challenges that need to be addressed before this technology comes to fruition. It can be argued that an efficient and reliable method needs to be developed for consistently inducing detonations. The scope of this research is to offer a more efficient and reliable method for producing these detonations in contrast to current approaches.

Previous studies, with regards to safety in nuclear power plants, have revealed that bluff-body obstacles in the path of confined reacting flow are direct contributors to deflagration-to-detonation transition (DDT)[3]. The confined nature of the configuration leads to the establishment of a compressible flow downstream of the flame that is caused by the deflagration wave. Turbulence/flame interactions can lead to an increase in heat release through flame wrinkling as well as through enhanced mixing and transport within the flame. Regions of intense combustion due to turbulence and/or shock reflections may lead to a transition to detonation through the proposed SWACER mechanism[4]. Those who have wished to induce DDT, rather than prevent it, have generally considered ways to maximize turbulence production, for instance, using high blockage ratio (BR) obstacles. These studies have focused on shortening DDT distances, but have suffered significant total pressures losses in the process[1]. These large obstacles have also acted as a thermal reservoir, adding and subtracting heat at improper times in the PDE's cycle. This is often referred to as "heat soaking"[5, 6]. Estimates of the thrust degradation associated with typical DDT-inducing devices range from 10% to 35%, depending on tube wall temperature and type of obstacle used[6-8]. While combustion control is achieved at the design point, physical obstacles have a fixed geometry that ultimately make them incapable of adapting to various inlet conditions. Their passive control and lack of adaptability make them less desirable in practical propulsion applications.

Given the significant total pressure losses, heat soaking and inability to adapt, alternatives to physical obstacles have been explored. Previous studies have shown the ability of a jet in crossflow (JICF) to act as a *virtual* bluff-body obstacle for flame holding[9]. This led to recent exploratory research regarding the ability of a JICF to accelerate confined unsteady premixed flames[10]. Evidence of enhanced turbulence production and flame acceleration was observed. Although not measured, total pressure losses were assumed to be reduced due to the lack of form drag commonly associated with physical obstacles. In opposition to a passive control approach previously discussed, a JICF is a type of active combustion control. The blockage created by the jet could be altered by adjusting the pressure driving the jet[9].

The present research involves experimental comparisons between physical and fluidic obstacles. Design of the fluidic obstacle came from the knowledge that the amount of blockage created by the protrusion of a physical obstacle likely determines its effectiveness. Using this principle, penetration of the jet into the main flow was deemed most important. It was then anticipated that simulating a physical orifice plate should provide the greatest blockage, and therefore the greatest influence on the advancing flame front. Simulation of a physical orifice plate using fluidics was achieved by constructing a thin slot jet around the tube. In future discussions, virtual obstacle will be replaced with fluidic obstacle or fluidic orifice plate. Below is a graphical representation of the recirculation regions created by a bluff body orifice plate (a) and a fluidic orifice plate (b).

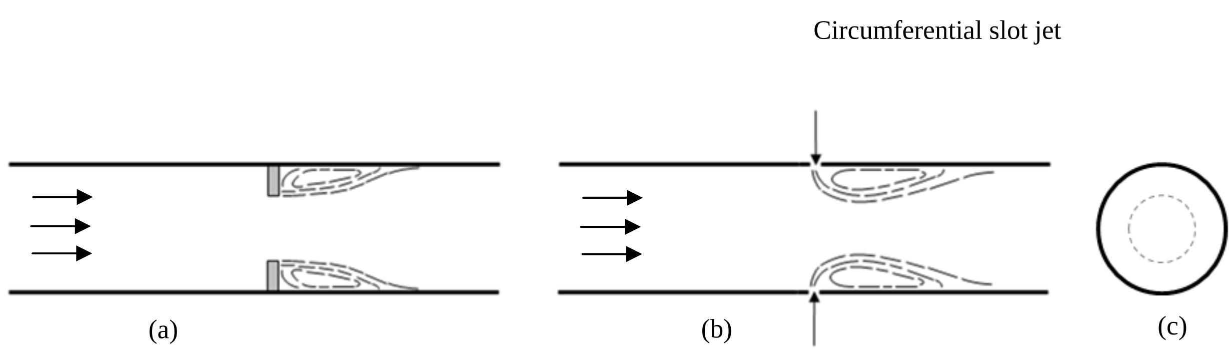

Figure 1 – Graphical representation of (a) physical orifice plate (b) fluidic orifice plate (c) side view

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II. Experimental Facility

Experiments were conducted within the Detonation Engine Research Facility (DERF) owned by the Air Force Research Laboratory (AFRL) at the Wright-Patterson Air Force Base (WPAFB) and operated by Innovative Scientific Solutions Inc. (ISSI). The AFRL PDE test bed consisted of an automotive engine head capable of delivering pulsed fuel/air mixtures at the desired equivalence ratio, pressure, temperature and frequency. This facility is described in detail elsewhere[11]. Schedule 40 pipe, measuring 87 inches in length and 2.07 inches inner diameter, was used as the detonation tube. The leading edge of each obstacle was axially located 13 inches downstream from the head end of the tube. A physical orifice plate and fluidic orifice plate were designed with the same bolt pattern to easily and quickly change the configuration. Figure 3 displays the location of the obstacles with the fluidic orifice plate installed. The PDE was operated at 15 Hz with an ignition delay of zero milliseconds.

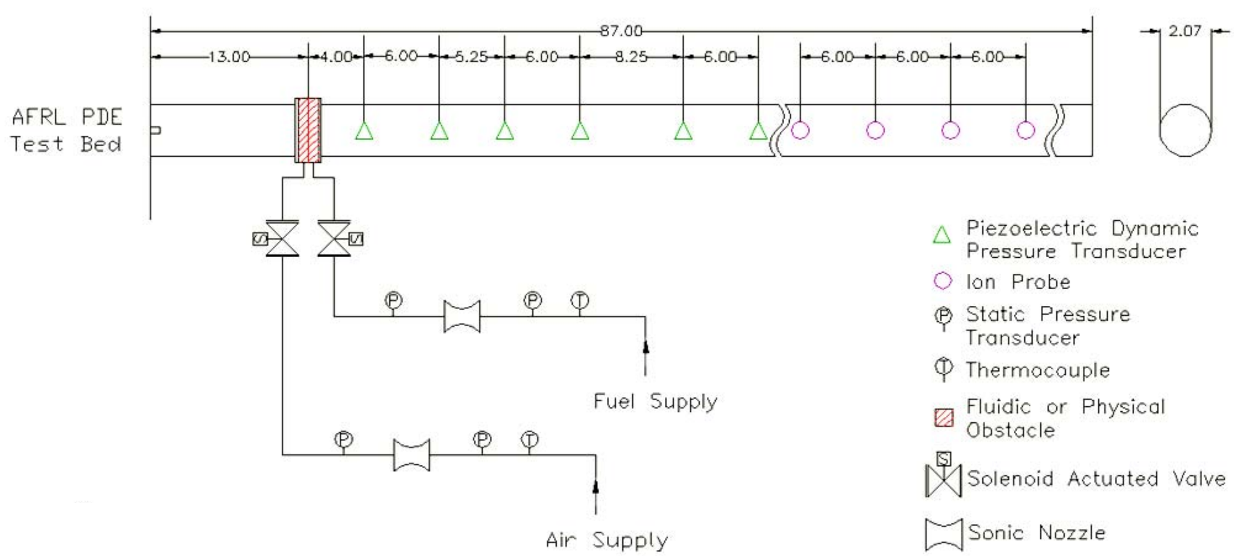

Figure 2 – Schematic of experimental setup

The fluidic orifice plate's supply came from an external hydrogen trailer and several high-pressure air bottles located beneath the test section. Metering of the flow of the fuel and air was accomplished through the use of sonic nozzles, static pressure transducers and thermocouples. Solenoid actuated ball valves, operated from a remote control center, initiated activation of the fluidic orifice plate. The fluidic orifice plate was operated in a continuous manner. Pulsing of the fluidic obstacle, much like the main flow, is expected to be necessary for real-world applications.

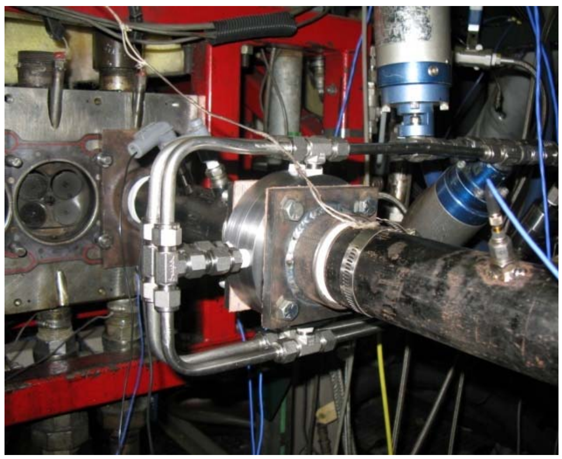

Figure 3 – close-up of fluidic orifice plate configuration

III. Measurement Methods and Data Analysis

A. PDE Measurements (Unsteady Reacting Flow)

Six dynamic pressure transducers and four ion probes, located axially along the tube, were used to calculate the DDT distance. Figure 2 provides dimensions for the location of these measurement devices. Dynamic pressure transducers were used near the obstacle to provide more information than obtained with ion probes alone. The pressure transducers were able to measure precursor shock speed as well as indicate a detonation. A computer program analyzed the pressure trace obtained from a high-speed data acquisition system. The program then marked the time when the trace exceeded a

given voltage threshold. These times were used in conjunction with the distance between them to obtain average velocities. Traces indicative of a detonation will exhibit an impulse representative of the Von-Neumann spike and a subsequent Taylor expansion. Ion probes were positioned downstream of the dynamic pressure transducers to verify

transition to detonation. An ion probe consists of a voltage potential across two leads protruding slightly into the detonation tube. The resistance across the two leads is reduced when a combustion front passes due to the ions present in the reaction zone. A drop is observed in the voltage history that corresponds to the combustion front being present at that ion probe's location. Recording the flame signature in the ion probe's voltage history and the distances between them enables the calculation of average velocity. The DDT distance was obtained by using the calculated average velocity and distance between two probes and linearly interpolating to find the position that corresponds to a CJ detonation velocity. In all calculations, 1960 m/s was assumed as the CJ detonation velocity for the stoichiometric hydrogen/air mixture.

Ignition time was measured using a piezoelectric dynamic pressure transducer located at the closed end of the PDE tube. A high-speed data acquisition system sampling at 1 MHz was used to record the voltage output history from the pressure transducer. A computer program filtered the pressure trace using a Savitsky-Golay filter. Starting at the time of spark discharge, the program calculated the slope of a 600 point window via linear regression. Advancing through the trace one point at a time, the program searched for a 5 V/s slope within the 600 point window. The center of this window was recorded as the ignition time. A detailed description of the data acquisition system has been described elsewhere[11]. Physically, ignition time is defined as when the flame kernel due to spark discharge in the reactive mixture reaches a substantial size. While "substantial" is a bit subjective, measurement of the ignition time was consistent throughout these experiments. Quantitatively, we have defined substantial to be 5 V/s slope within a 600 point window of the dynamic pressure transducer output voltage history.

B. Non-Reacting Steady Flow Measurements

The total pressure loss was obtained using steady flow through the experimental setup. Static pressure transducers were located at the beginning and end of the tube. A flow straightening section was used prior to the entrance of the experimental setup to ensure consistent inlet conditions. The dynamic pressure was calculated using the mean velocity obtained from the known inlet mass flow rate and area along with an estimated density.

Turbulence intensity measurements were obtained using hot-film anemometry. Steady flow through the experimental setup was used to represent instantaneous conditions. The upstream and downstream probes were axially located four inches from the center plane of the obstacle. The probes were then positioned in the center of the tube and

oriented to obtain turbulence intensity measurements in the direction of the bulk flow. The hot-film anemometer was calibrated using a pitot-static probe and King's Law[12].

IV. Results and Discussion

A. PDE Results (Unsteady Reacting Flow)

1. Ignition Time

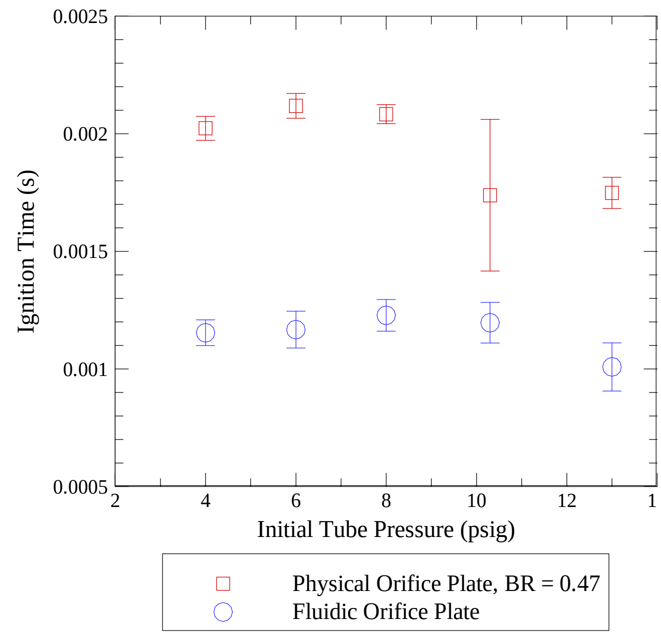

Figure 4. Comparison of ignition times for a fluidic and physical orifice plate.

Ignition time is defined as the elapsed time from spark discharge to the development a substantial flame kernel. Naples et al. have shown there to be a dependence of ignition time on initial tube pressure[13]. Therefore, it was essential to measure ignition time for various initial tube pressures. From Fig. 4 a majority of the data points collected provided evidence that a fluidic orifice plate reduces ignition time by approximately 45%. It is vital to PDE performance that all phases of its cycle be shortened as much as possible. A reduction in cycle time allows operation at a higher repetition rate and therefore greater thrust. Schauer, Stutrud, and Bradley have shown there to be a linear dependence of a PDE's thrust on its firing rate[11]. An explanation for this decrease in ignition time is provided by the hot-film data. Figure 9 provides upstream turbulence intensity measurements, to both obstacle configurations, using hot-film anemometry. While these measurements were taken during steady flow, and the PDE's flow field is highly unsteady, the results are indicative of instantaneous conditions. It is important to note the three momentum ratios listed on Fig. 9. Momentum ratio is defined as jet momentum to main flow momentum. For high momentum ratios, it is believed that turbulence has been propagated upstream due to the impinging nature of the fluidic orifice plate's design. Turbulence is an effective method for convective transport, increasing the flame's surface area and therefore heat release rate. Turbulence levels are high near the head of the PDE, enabling the flame kernel to quickly develop. Comparing T.I. levels for the fluidic and physical orifice plates at the lowest Reynolds number tested, there is a noticeable difference in values. Conservatively, a 60% increase in upstream

turbulence intensity is observed for the fluidic obstacle configuration. It is likely that this is the main contributor to the reduction in observed ignition time. Due to the knowledge that ignition time is inversely related to initial tube pressure, it was essential to measure the increase in tube pressure due to the additional mass injected into the tube. Tests revealed a maximum of one-half psi increase in tube pressure due to the addition of the fluidic material. This increase in tube pressure is far too small to explain the drastic decrease in ignition time. We can therefore conclude that the reduction in ignition time is attributable to the increase in upstream T.I. levels, relative to the fluidic obstacle, during the fill portion of the PDE's cycle.

2. DDT Distance

Deflagration-to-detonation transition distances have been obtained for varying initial tube pressures and obstacle configurations. Previous studies have shown the relationship of DDT distance to initial tube pressure to be inversely related. The data shown in Fig. 5 compares the effectiveness of the two obstacles in producing a detonation. Shorter DDT distances are indicative of greater effectiveness. A shorter distance required to transition a flame to detonation will decrease cycle time and weight of a PDE. It has been shown that there are multiple pathways from deflagration to detonation[4]. The DDT process is not unique in the sense that different events can lead up to a detonation. Urtiew and Oppenheim have observed DDT in several regions relative to the flame. Their schlieren images have shown DDT occurring, within the precursor shock, between the flame brush and the precursor shock, and even within the flame brush itself[14]. It is understandable that it is difficult to obtain low scatter in DDT distance

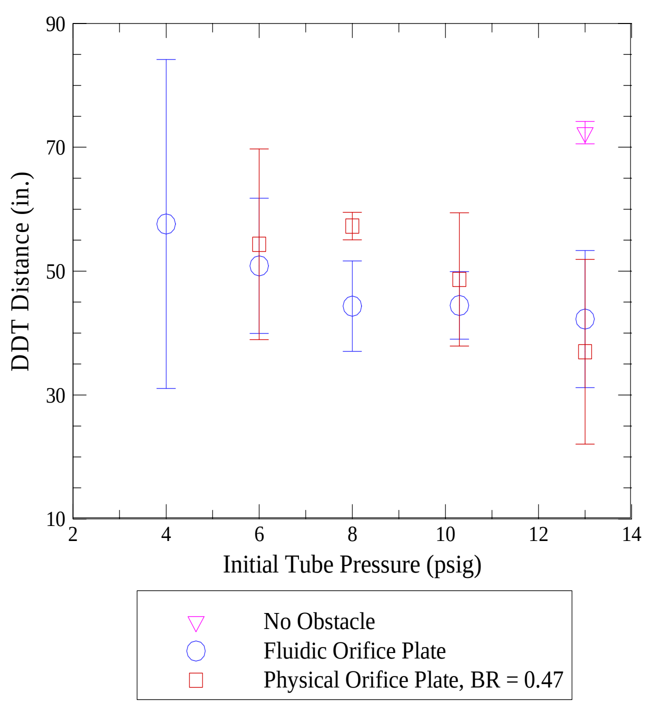

Figure 5. Comparison of DDT distances for a fluidic and physical orifice plate.

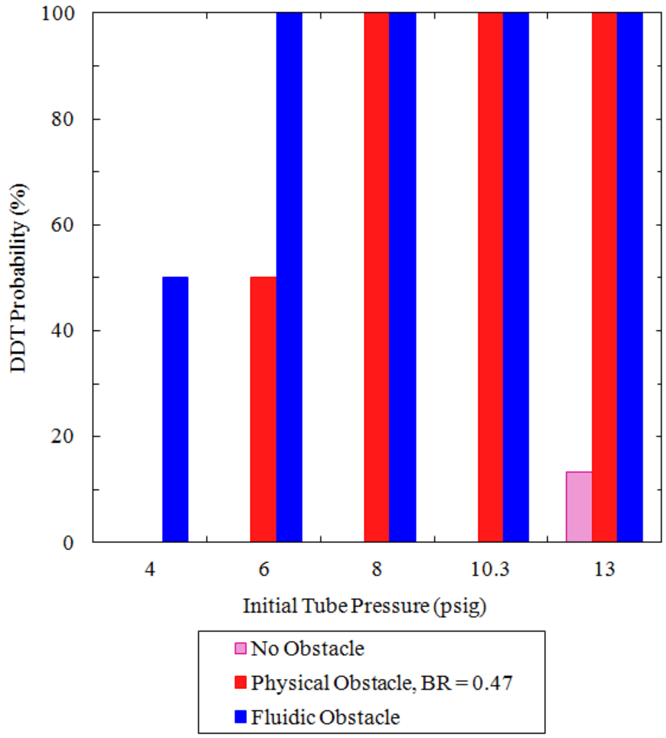

Figure 6. DDT probabilities pertaining to results in Fig. 5

when the DDT process is inherently highly stochastic. The large scatter in the data has reduced the comparison of the two configurations although it is apparent that the DDT distances are generally comparable. Future efforts are expected to encompass an increase in sample size for both configurations that may lead to a more definitive conclusion. Due to the infancy of fluidic obstacle technology, obtaining DDT was viewed as a major success. To illustrate the sensitivity of the stoichiometric hydrogen-air mixture used in this study, and its relationship to initial pressure, DDT distances were measured for a smooth tube as well. In a smooth tube, DDT was achieved only for the highest initial tube pressure tested. By using obstacles at this pressure, a reduction in DDT distance by almost 50% was achieved.

Another measure of effectiveness is the probability of each configuration to successfully transition a flame from deflagration to detonation. Figure 6 indicates that the fluidic orifice plate had a higher probability of producing a detonation at lower initial tube pressures than the physical orifice plate. It is interesting to note that the fluidic orifice plate was able to produce a detonation at an initial tube pressure of four psig while its physical counterpart could not. At 13 psig initial tube pressure, DDT in a smooth tube occurred only 13%. This further illustrates the stochastic nature of the DDT process.

3. *Fluidic Obstacle Composition*

$$y = 46 \text{ in.} + \sec\left(\frac{\pi(x \text{ psig} - 119 \text{ psig})}{180 \text{ psig}}\right) \text{ in.}$$

The effect of the composition of the injection material through th[...]red by using pure air in addition to the same mixture used in the main tube. Because injection of the fluidic obstacle was continuous, the fill mixture of the PDE was subjected to the added material of the fluidic obstacle. When using the same stoichiometric mixture in both the main tube and fluidic orifice plate, there would be no alterations to the fill mixture's equivalence ratio. Using air as the injection fluid resulted in a leaner mixture and was likely heterogeneous. It is expected that short residence times during the fill cycle would lead to inhomogeneities of the resulting fill mixture. A conservative estimate of the main tube equivalence ratio, which was initially unity, resulting from constant fluidic injection of pure air was approximately 0.8. This was calculated using the known mass flow rate of the fill cycle and the known fluidic mass flow rate at the highest injection pressure tested (207 psig). From Fig.7, there is no discernable difference in DDT distances between a fluidic composition of air and a H_2/air mixture.

The effect of varying injection pressure was also briefly explored using air as the fluidic obstacle composition. Figure 7 shows that no DDT was observed for injection pressures lower than approximately 115 psig. The flame speed data (not shown) revealed that acceleration was still achieved using injection pressures lower than 115 psig. At around 105 psig, a maximum flame speed of 1340 m/s was measured.

B. Non-Reacting Steady Flow Results

1. Total Pressure Loss

Estimates of the total pressure loss due to a single obstacle were obtained using steady flow for three obstacle configurations. Figure 8 displays the estimated total pressure loss as a function of Mach number exiting the tube. All three configurations show a second-order

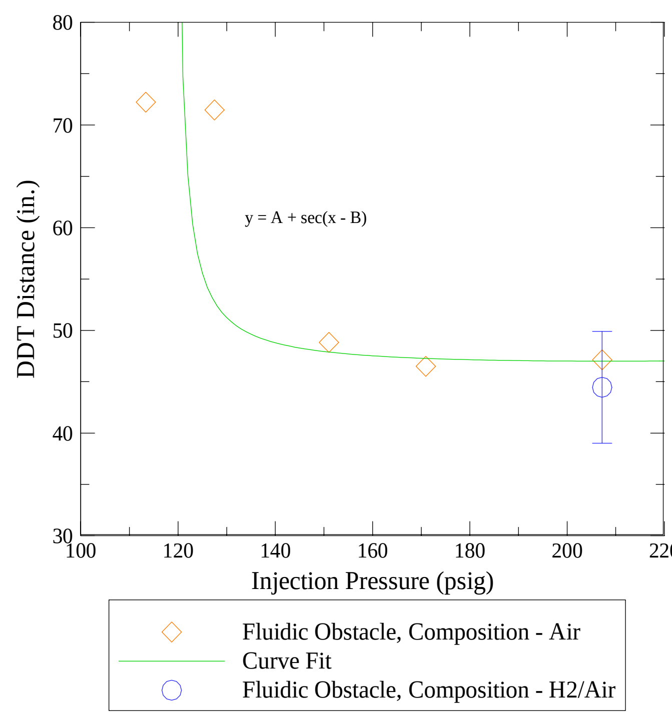

Figure 7. Comparison of DDT distances using fluidic obstacle composition of air and stoichiometric H_2/air

polynomial dependence of the total pressure loss on the exit Mach number. The physical orifice plate, of blockage ratio 0.47, exhibits a much higher total pressure loss compared to that of the fluidic obstacle. Here, the fluidic obstacle has been turned “off” but the apparatus is still in position. This configuration is essentially a smooth tube with a small cavity. This was seen as most applicable to how a fluidic obstacle would be used realistically. It is expected that the fluidic obstacle would be pulsed, much like the main flow. Towards the latter portion of the exit Mach numbers tested, the BR = 0.47 physical orifice plate suffers significantly greater total pressure losses than those observed by the fluidic configuration. While these data are not thrust measurements directly, reduction in thrust is attributable to total pressure losses. Total pressure losses are due to friction from wall roughness, pressure drag and other factors. The fluidic obstacle case is seen as the minimal total pressure loss possible given a fixed wall roughness. It is important to note that efforts have been made elsewhere to reduce total pressure losses while maintaining the idea of physical obstacles[6]. Though results for a physical orifice plate of BR 0.28 are given in this figure, these data are shown for qualitative purposes only. No other results for this configuration have been presented.

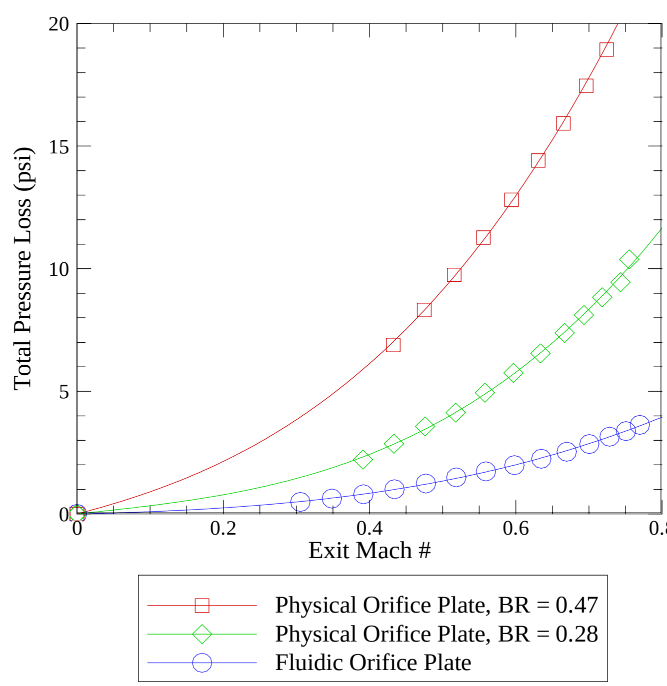

Figure 8. Estimated total pressure losses for different obstacle configurations

2. Turbulence Intensity

Turbulence intensity measurements were obtained for both orifice plate configurations. Steady flow was used to assess the abilities of each obstacle configuration to produce turbulence at various incoming Reynolds numbers. The characteristic length scale used in all Reynolds number calculations is the inner diameter of the tube. The variables, u' and U, are defined as the root-mean-square of the mean velocity and the mean velocity, respectively. In Fig. 9, momentum ratios have been listed as the momentum of the jet to the momentum of the main flow. At low upstream Reynolds numbers, the momentum of the jet is greater than that of the main flow. As stated previously, the fluidic obstacle's impinging design enables upstream conditions to be

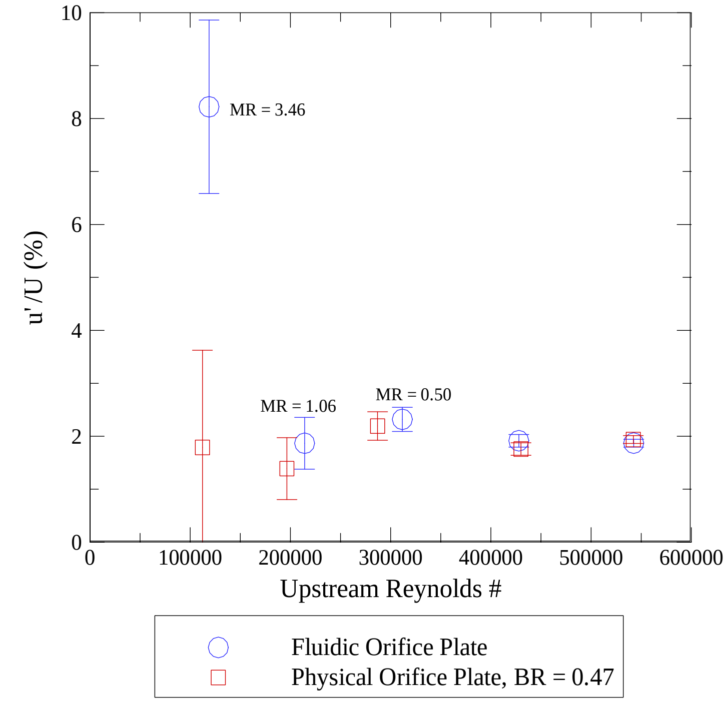

Figure 9. Centerline turbulence intensity measurements located 4 in. upstream of obstacle

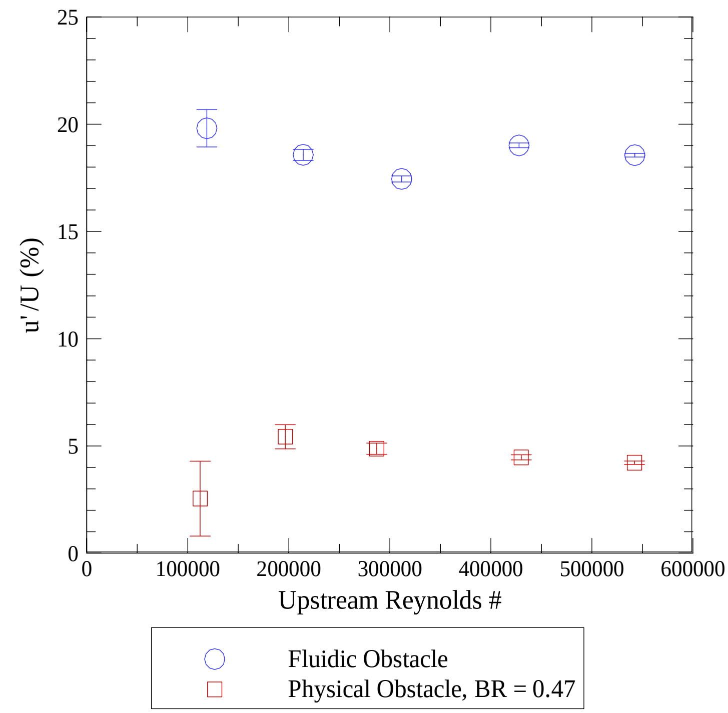

Figure 10. Centerline turbulence intensity measurements located 4 in. downstream of obstacle

disturbed by the high jet momentum. At MR = 1.06, the momentum of the jet and main flow are approximately equal. At this Reynolds number, the jet no longer has sufficient momentum to disrupt the upstream flow field. There exists little difference in turbulence intensity between the different configurations for Reynolds numbers higher than 200,000. Physical obstacles are only able to produce turbulence in their wake while an impinging fluidic design is capable of turbulence production upstream as well as in its wake.

There have been many studies that describe the role of obstacles, in the context of accelerating confined flames, as turbulence producing devices[3,15]. Their primary mechanism for accelerating a flame, particularly in the early stages of flame evolution, is generating large scale turbulence in the induced flow from the expansion downstream of the obstacle. Figure 10 displays downstream turbulence intensity levels generated from both obstacles. The fluidic orifice plate generates 240% greater T.I. levels than those produced by the physical orifice plate. High turbulence levels are expected due to the characteristics of a high velocity jet. Given this knowledge of a jet's potential for turbulence production, the role of physical obstacles as effective turbulence producing devices has been challenged. This potentially makes physical obstacles obsolete in, at the very least, the beginning section of a PDE. Of course, the role of obstacles transforms as the flame progresses further down the tube. Shock reflection can be argued as one of the most effective processes for bringing a localized region of reactants to a high enough pressure and temperature to promote formation of a detonation kernel.

V. Conclusion

The PDE's potential as a viable technology is dependent upon its ability to effectively produce detonations in a short distance with minimal losses. This research has proposed a more efficient and reliable method for transitioning confined flames from deflagration to detonation with the ultimate goal of using practical hydrocarbon fuels for application. A fluidic orifice plate has been suggested as an improvement upon conventional physical obstacles within the flow path. Utilization of reacting unsteady flow has revealed the ability of a fluidic obstacle to induce DDT with comparable distances to that of a physical obstacle. Non-reacting steady flow results have indicated the significant reduction in total pressure losses due to the lack of form drag commonly associated with bluff-body obstacles. Turbulence intensity measurements, taken upstream and downstream of both types of obstacles, have suggested that a fluidic orifice plate is superior in turbulence generation when compared to its physical counterpart. In addition, ignition time has been

reduced, which represents shorter cycle times leading to greater thrust. Future efforts are expected to pursue DDT using more practical hydrocarbon fuels.

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